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Yacht sail flow: recent findings and unanswered questions

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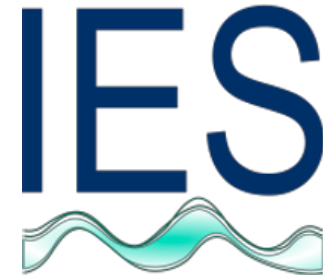
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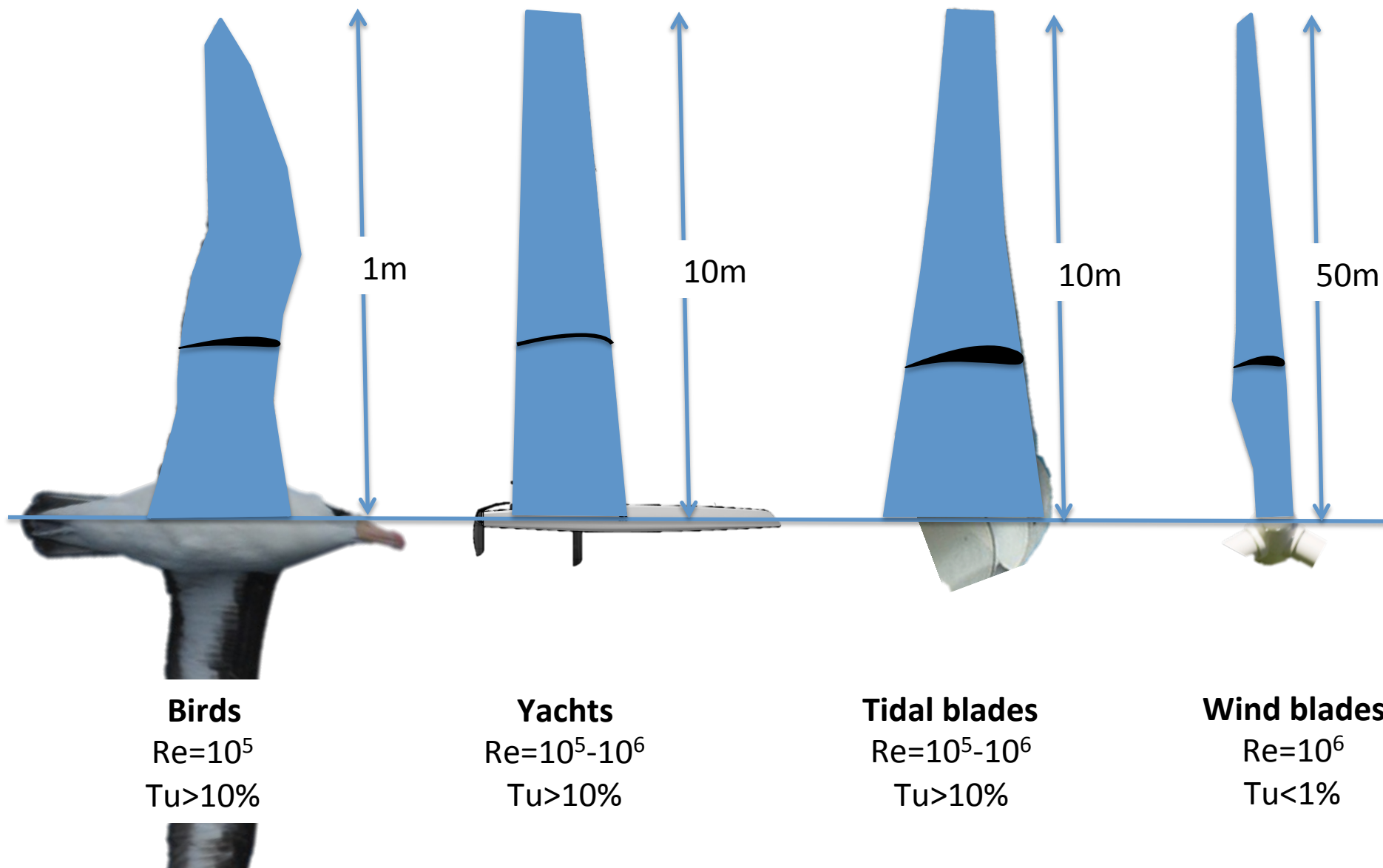
Yacht sail flow: Recent findings and unanswered questions

Dr Ignazio Maria Viola



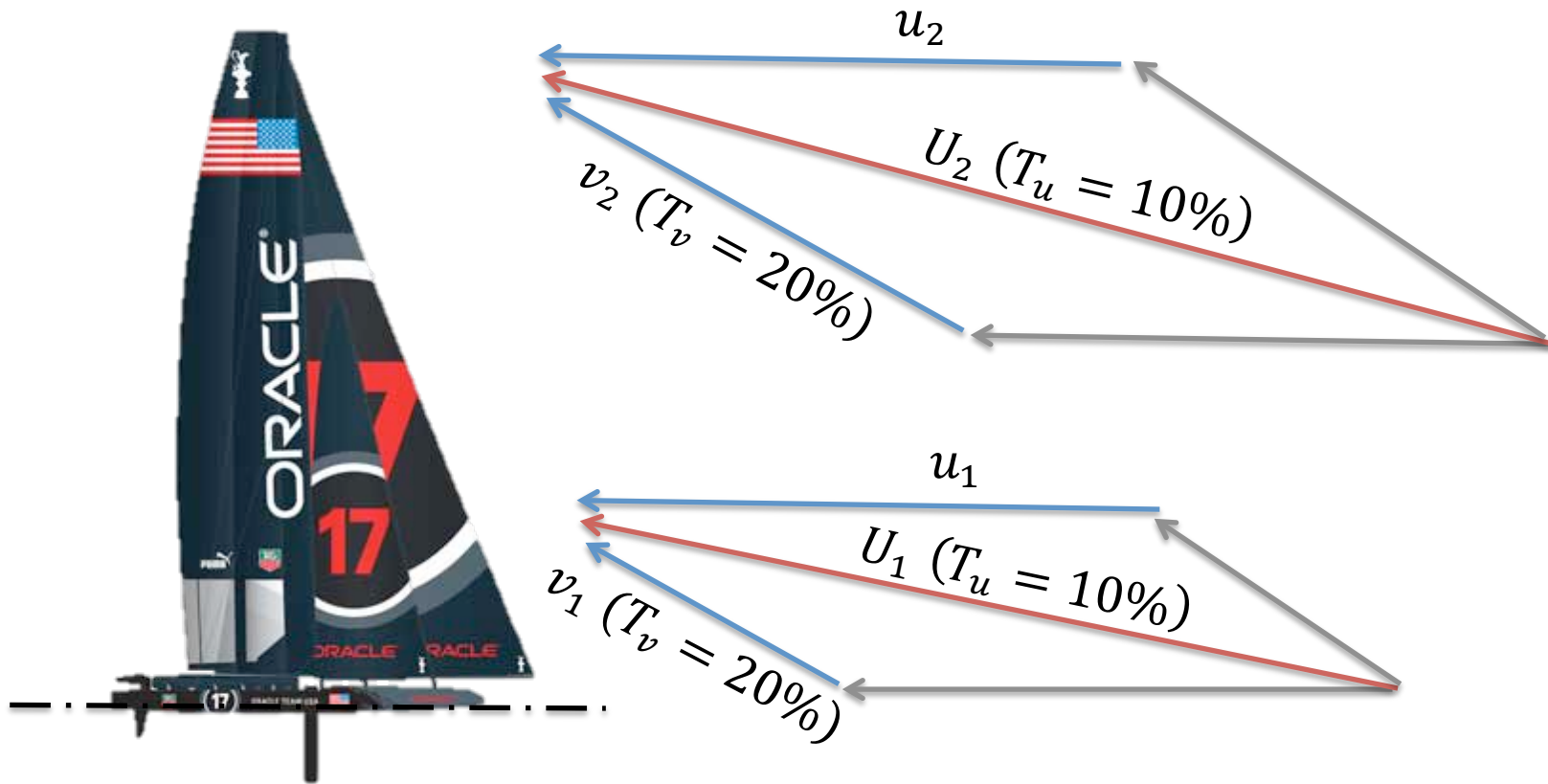
Sails

Sails are 3D wings operating at transitional Re in high turbulent conditions



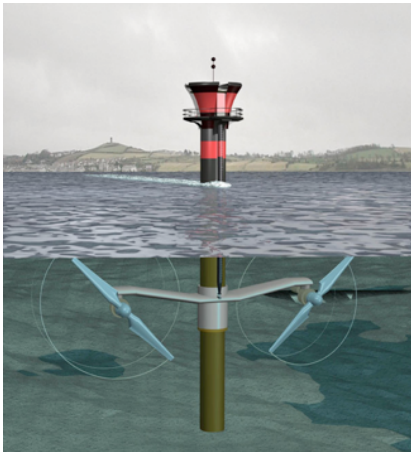
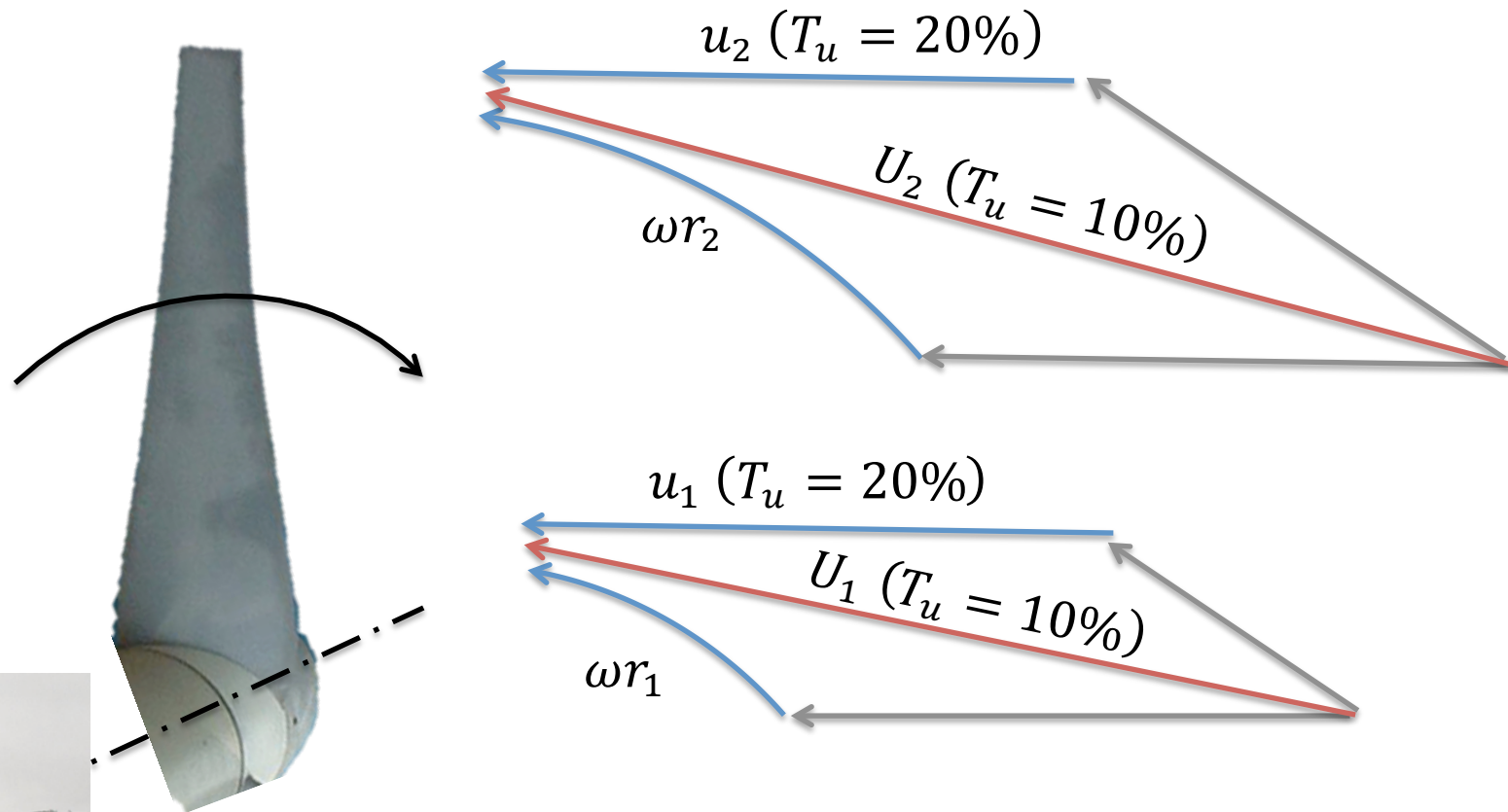


Spanwise velocity profile





Spanwise velocity profile



The spanwise velocity profile experienced by sails is the same as the one experienced by tidal turbine blades



Flexible

Fluid-structure interaction of sails is largely unknown
(follow Dr Matthieu Durand's work for future developments)





Thin

The extreme sharpness of the leading edge is what makes sail flow exceptional

SAIL

Thickness/chord= 10^{-4}



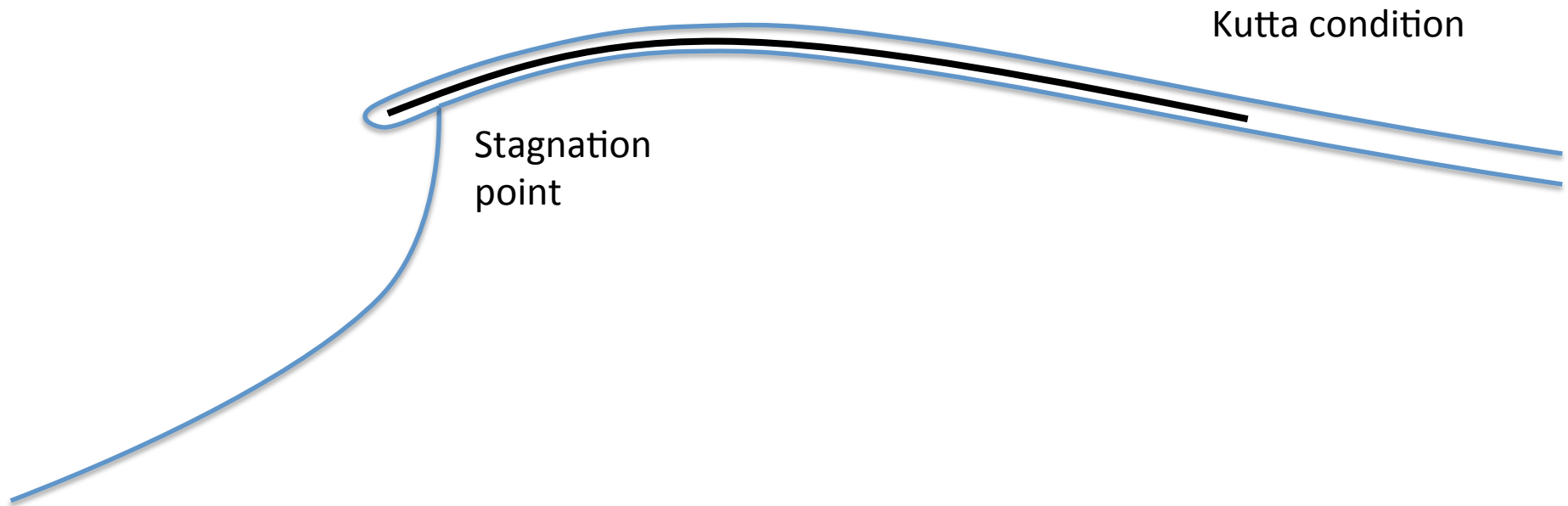
THIN FOIL

Thickness/chord= 10^{-2}





Potential flow interpretation





Combination of Laplace solutions

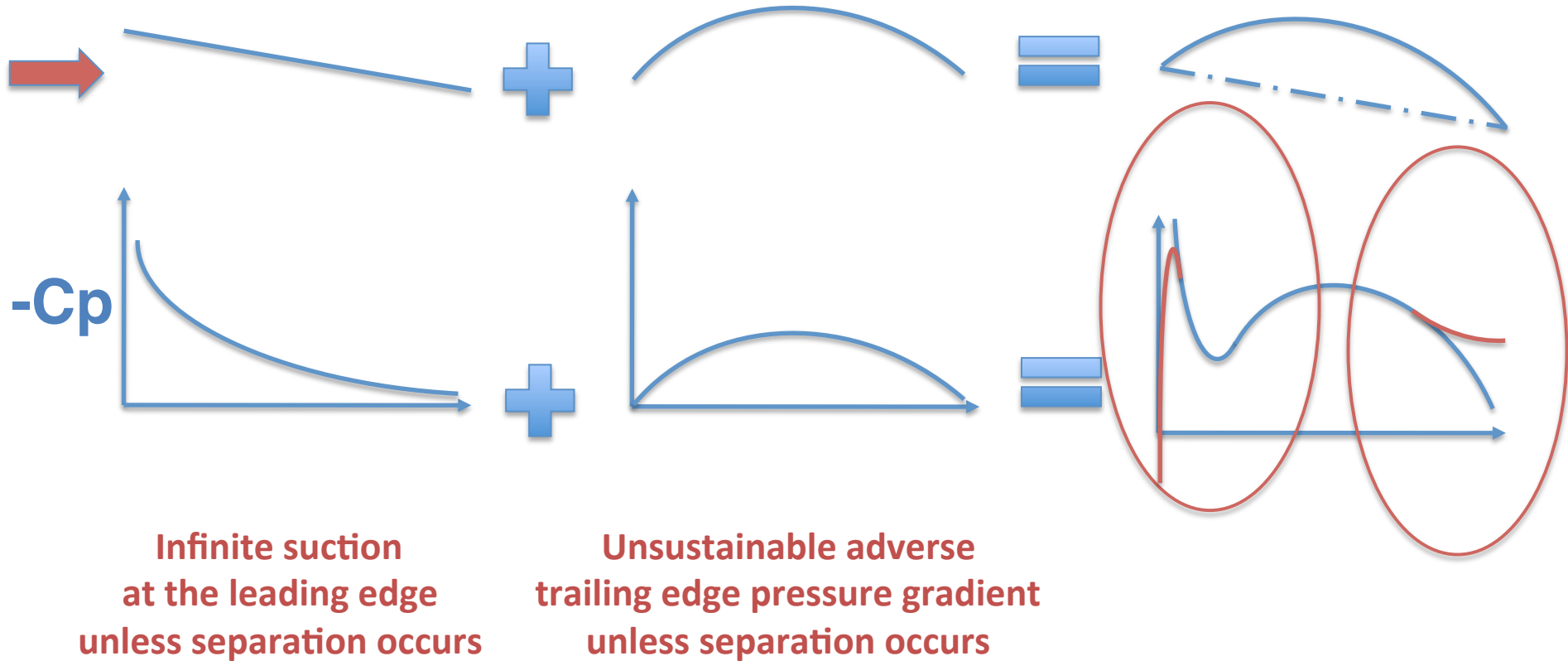
Flat plate
at incidence



Curved plate
at ideal angle of attack

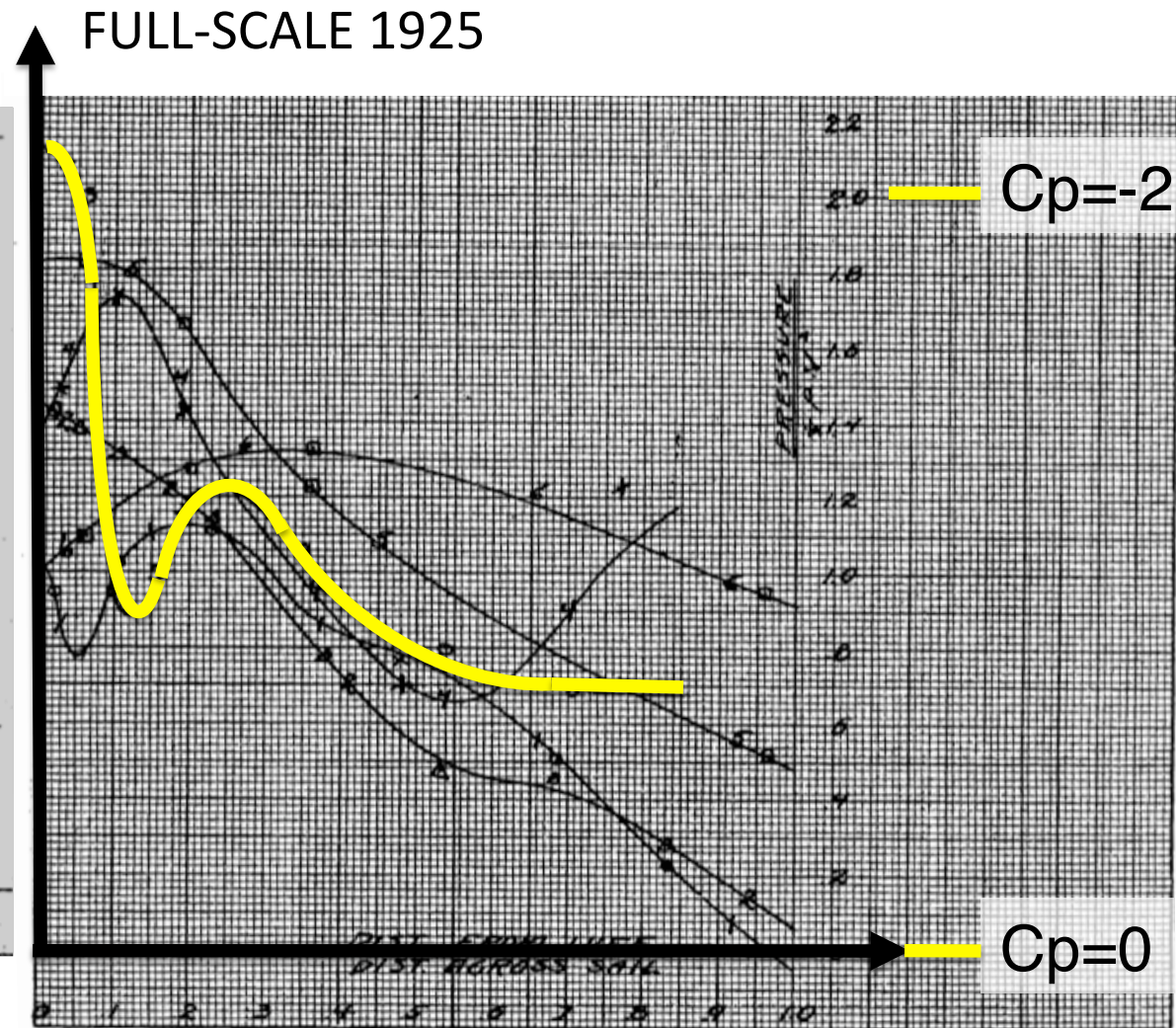
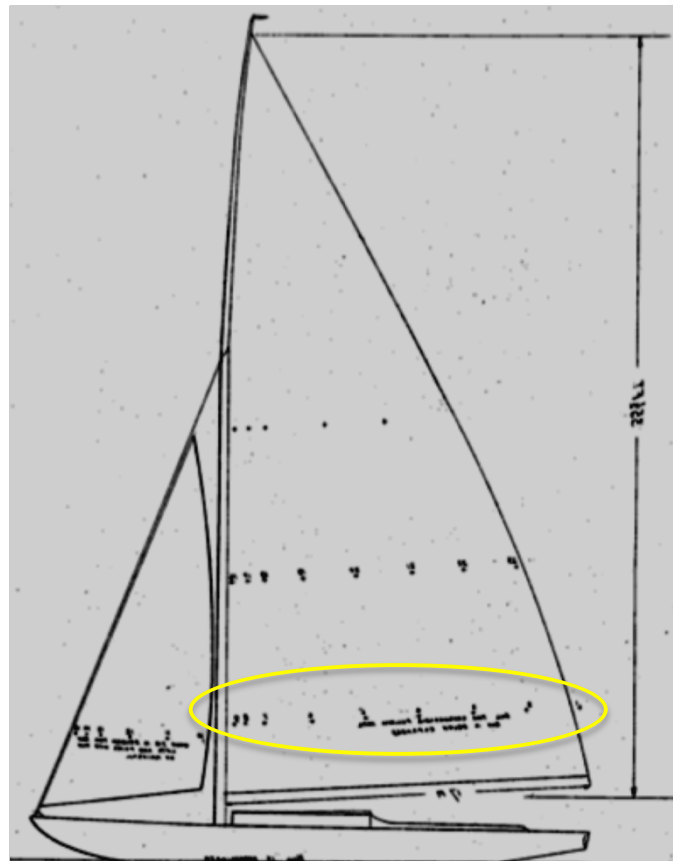


Sail
at incidence





Experimental evidence

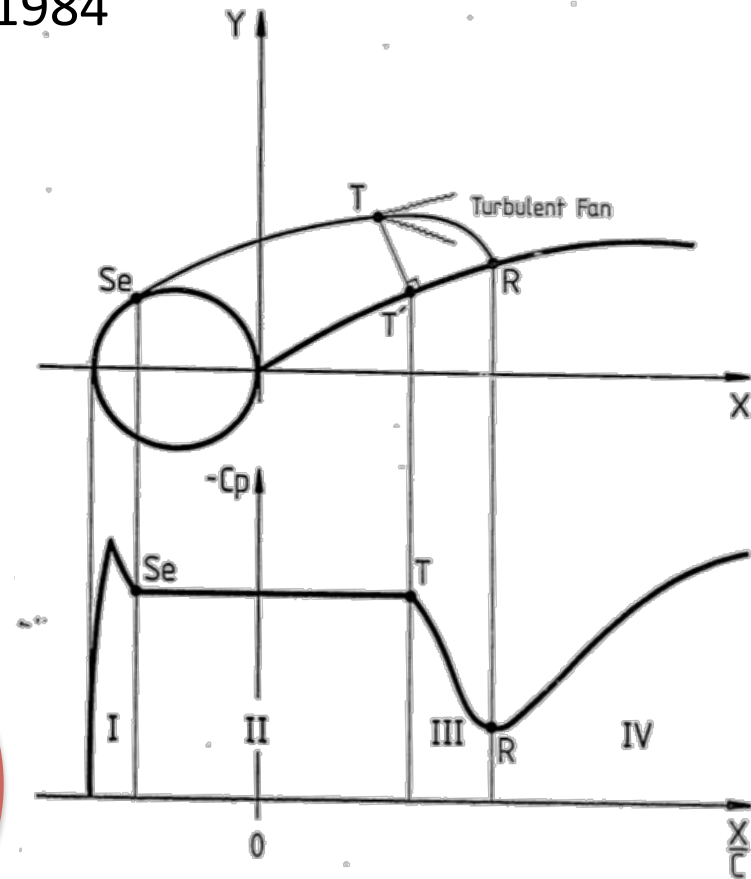
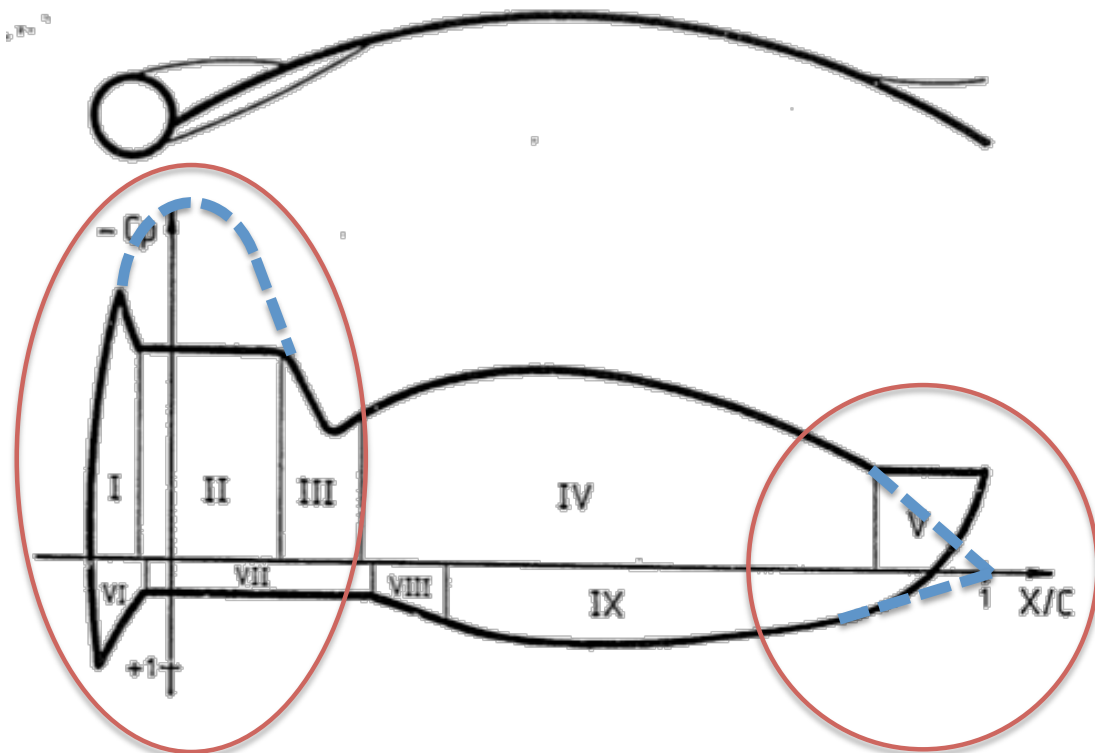


Warner EP & Ober S, 1925, The Aerodynamics of Sails, Soc. Nav. Arch. Mar. Eng., NY



Experimental evidence

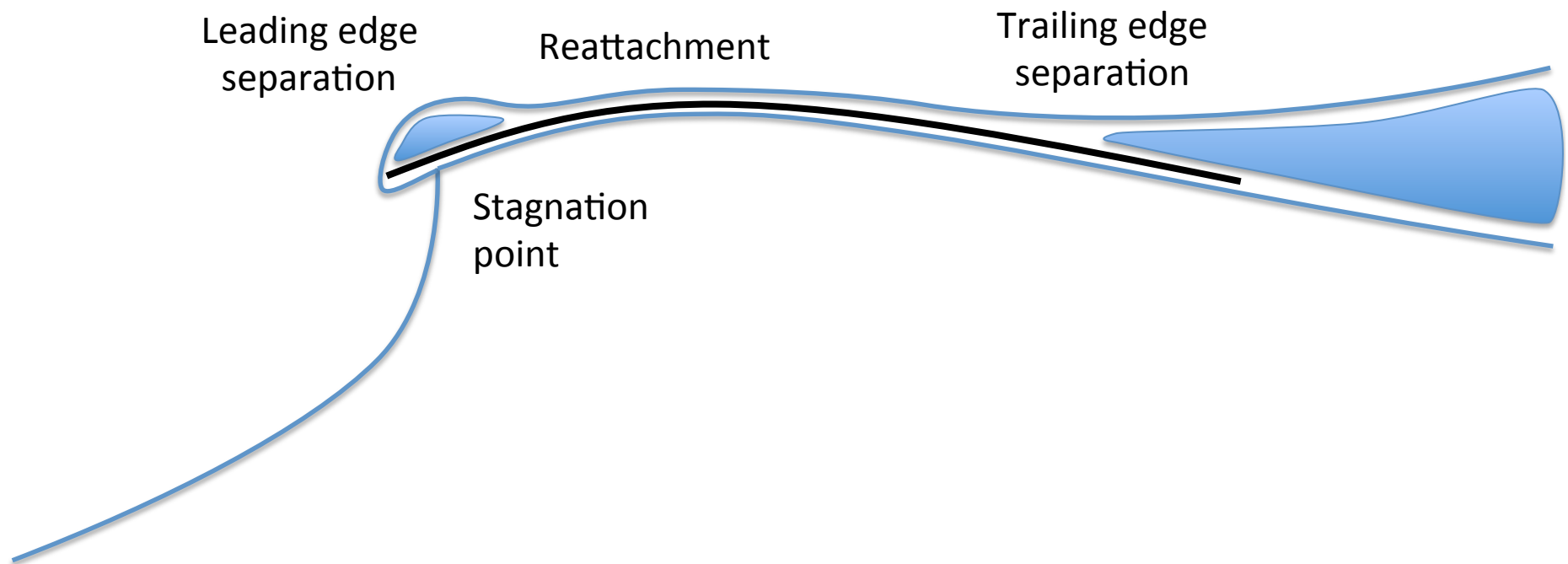
WIND TUNNEL 1984



S. Wilkinson, 1984, Partial Separated Flow Around Mast and Sail, *PhD Thesis, Univ. Southampton*



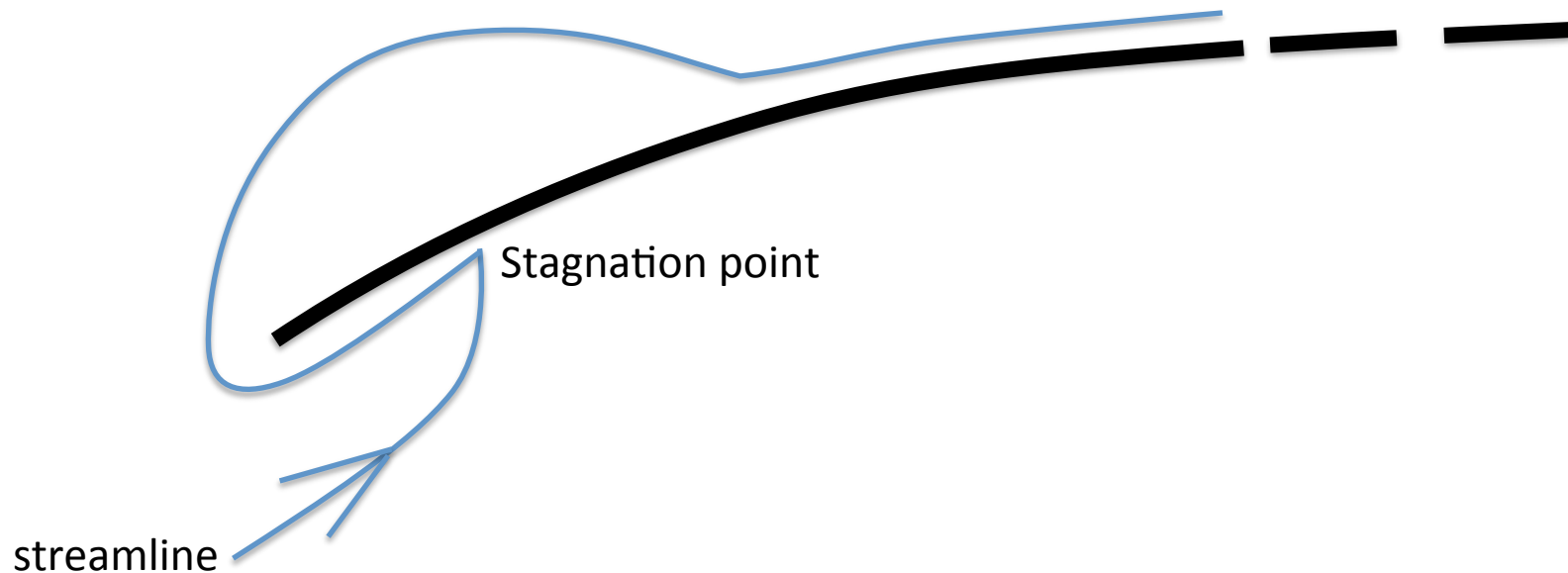
Viscous effects





Leading edge separation

- At an angle higher than the ideal angle of attack, the stagnation point must be on windward side (no exp evidence on sails)
- From the stagnation point to the leading edge the pressure decreases abruptly (highly favourable pressure gradient) and thus the boundary layer must be laminar (no exp evidence on sails)
- At the sharp leading edge the flow must separate (no exp evid. on sails)
- Full-scale and wind tunnel flow visualisation shows reattachment

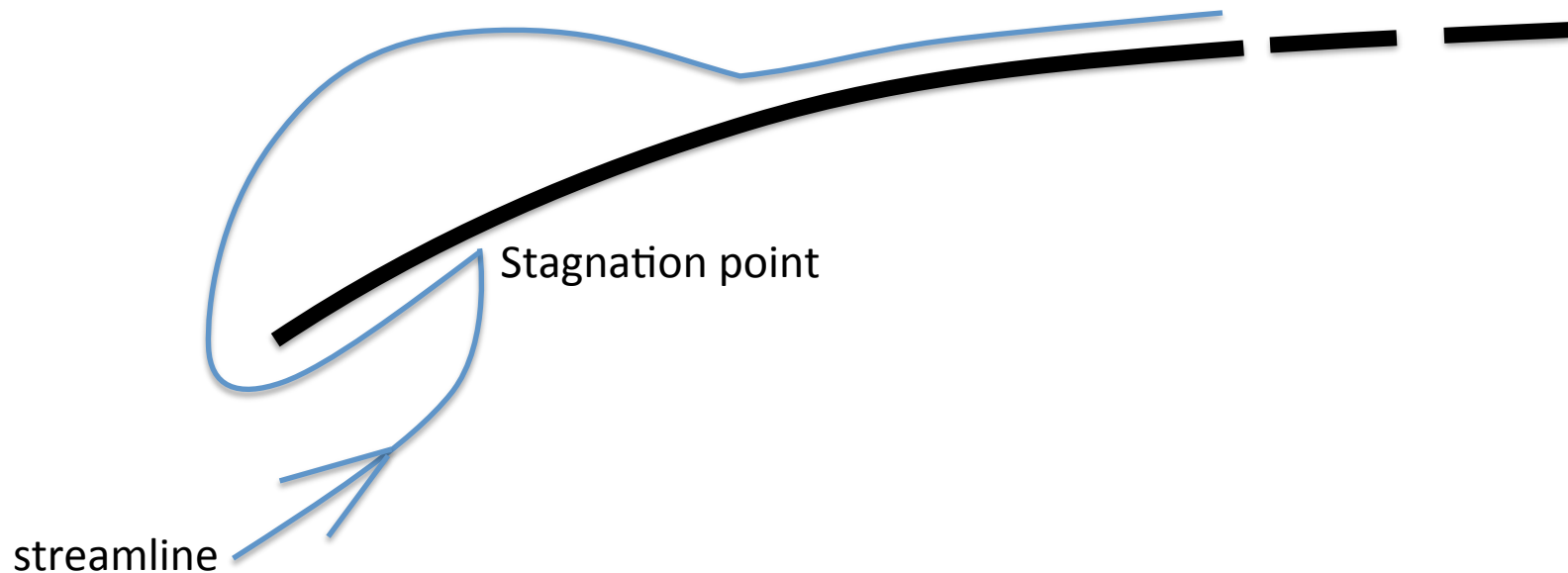




Leading edge separation

Given the Reynolds number at which sails operate:

- Transition is likely to occur in the separated shear layer
- Turbulence is likely to promote (time-averaged) reattachment
- This can lead to either:
 - (A) Laminar Separation Bubble
 - (B) Leading Edge Vortex



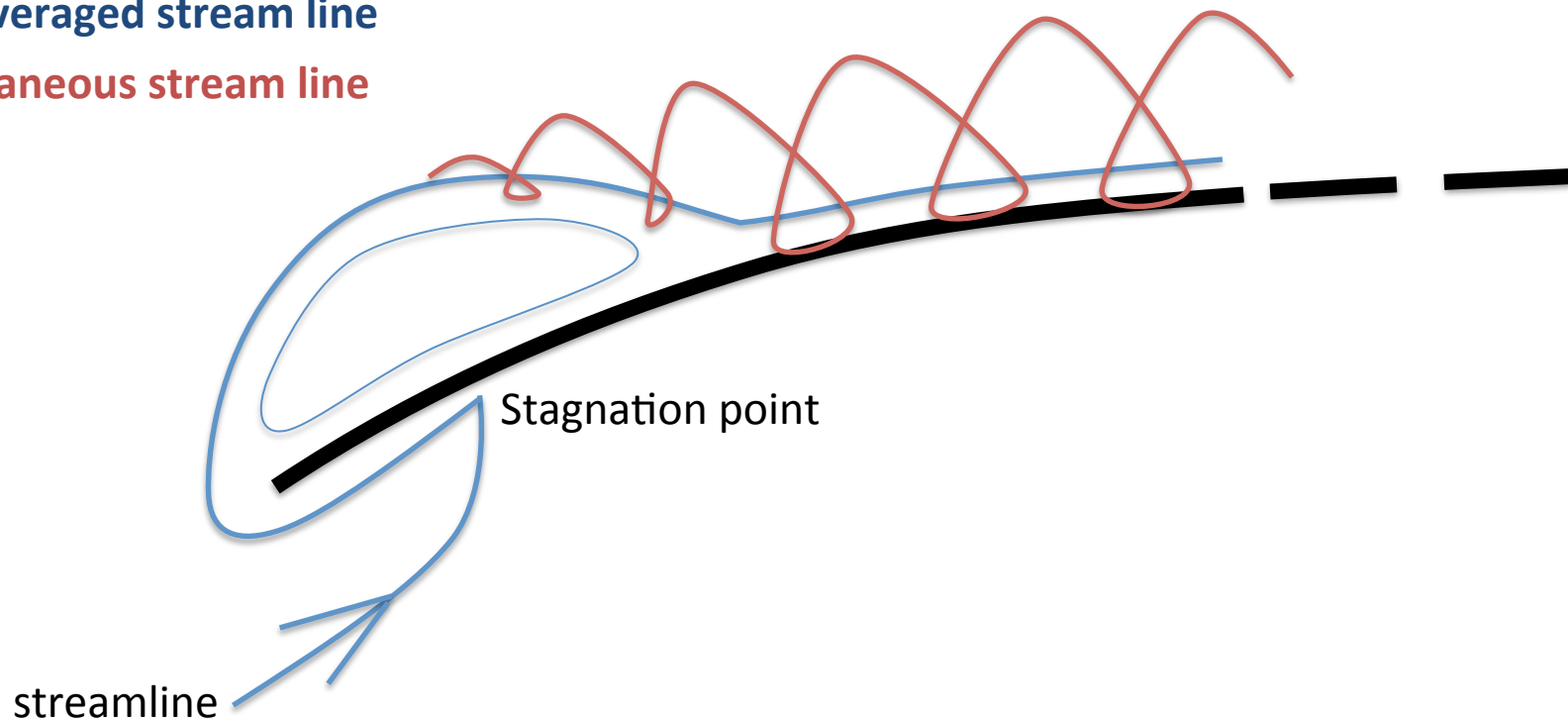


Laminar Separation Bubble (LSB)

- Discrete pockets of clockwise vorticity are generated from the separated shear layer and are convected downstream transferring momentum from the outer flow to the reattached boundary layer
- The reattachment downstream of the bubble is defined only in a time-averaged sense

Time averaged stream line

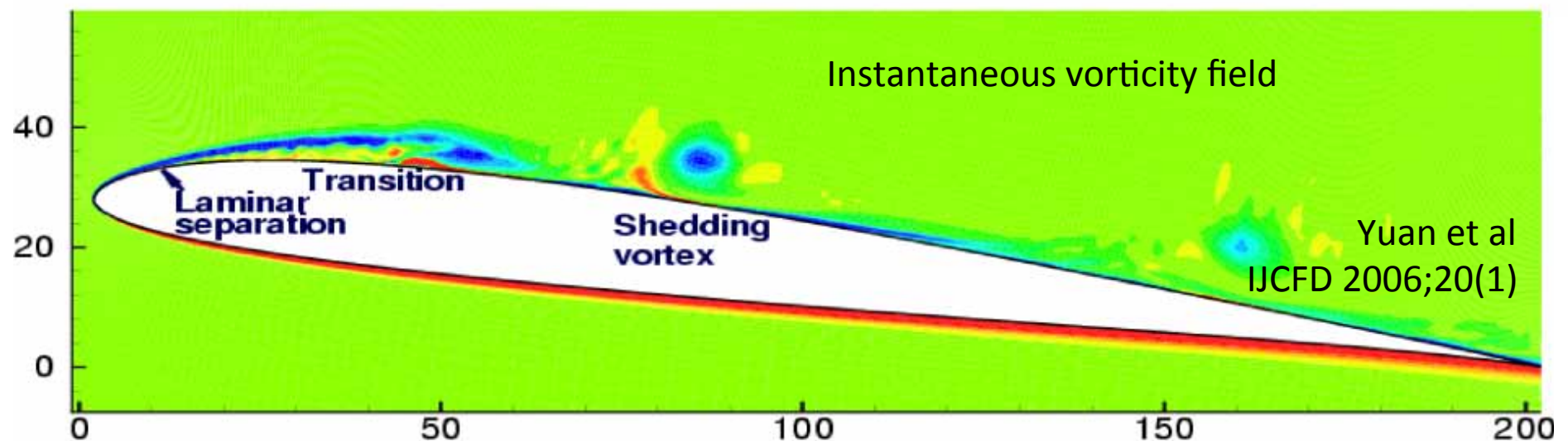
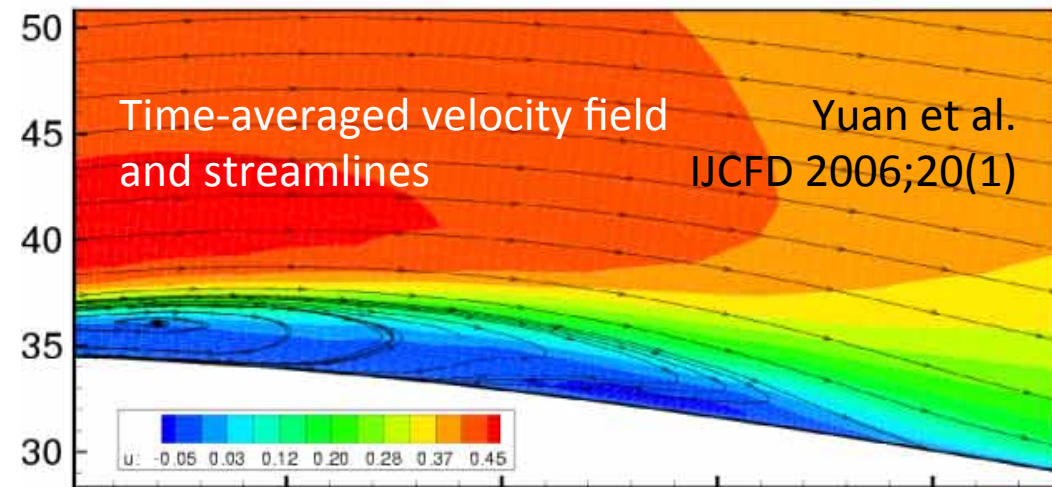
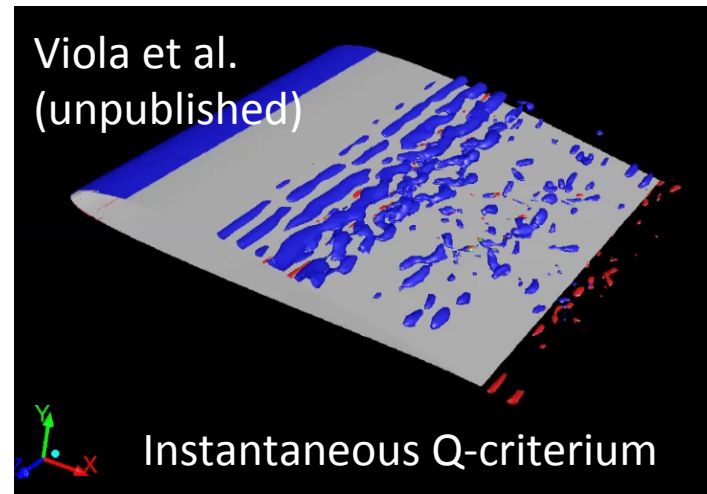
Instantaneous stream line





LSB on foils

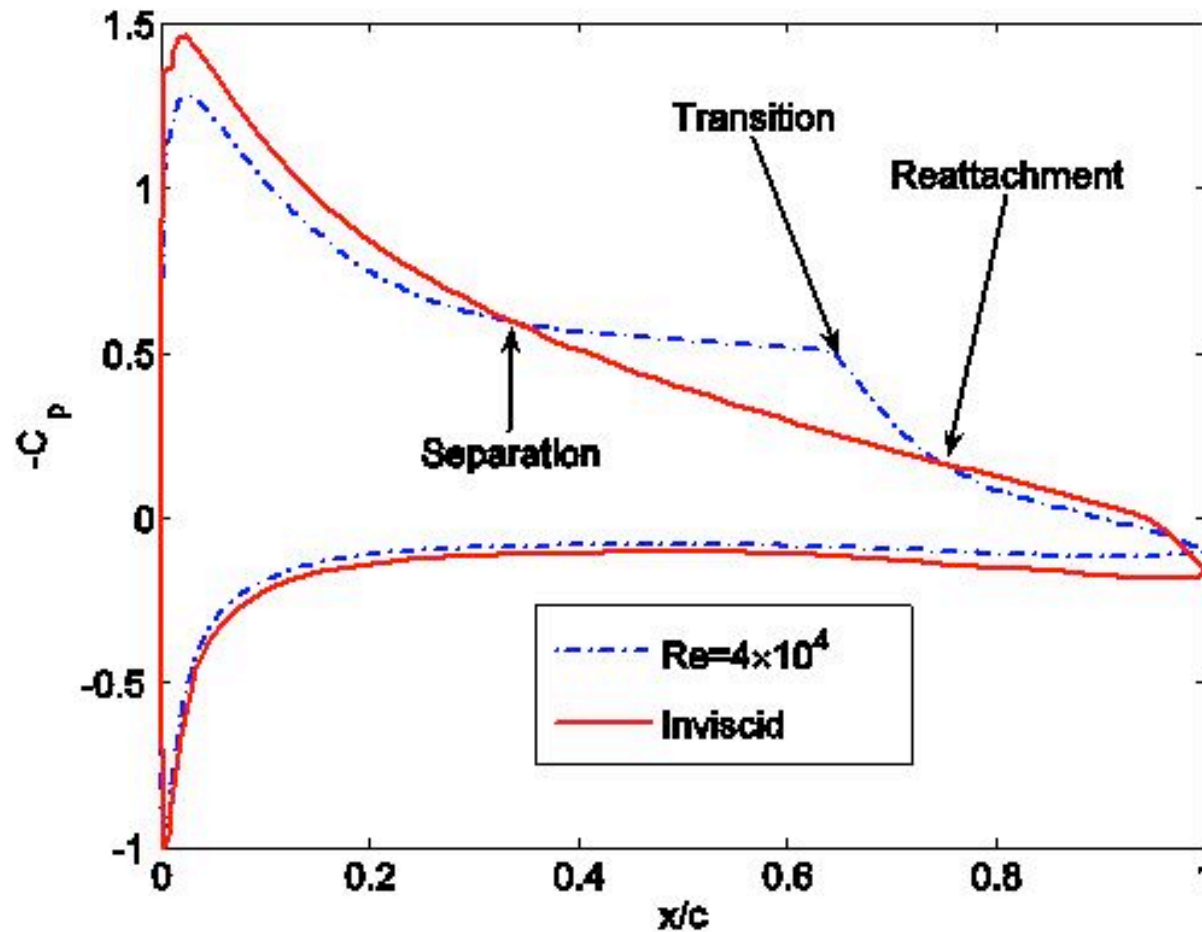
- The LSB occurs on foils at transitional Reynolds numbers ($10^5 < Re < 10^5$)





LSB on foils

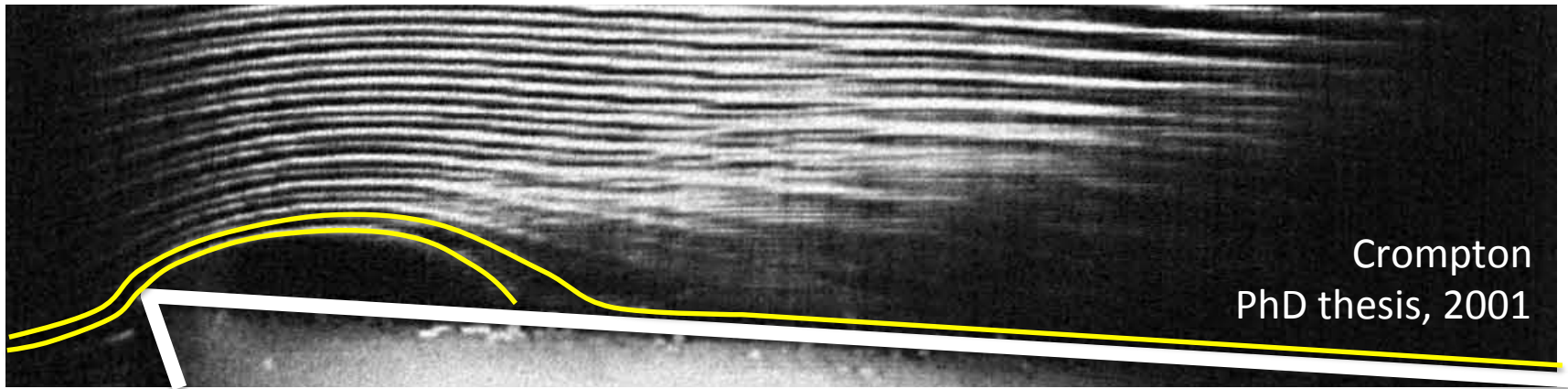
- The LSB on foils is characterised by low recirculation inside the bubble and a pressure plateau is observed in correspondence of the bubble





LSB on plates (long type)

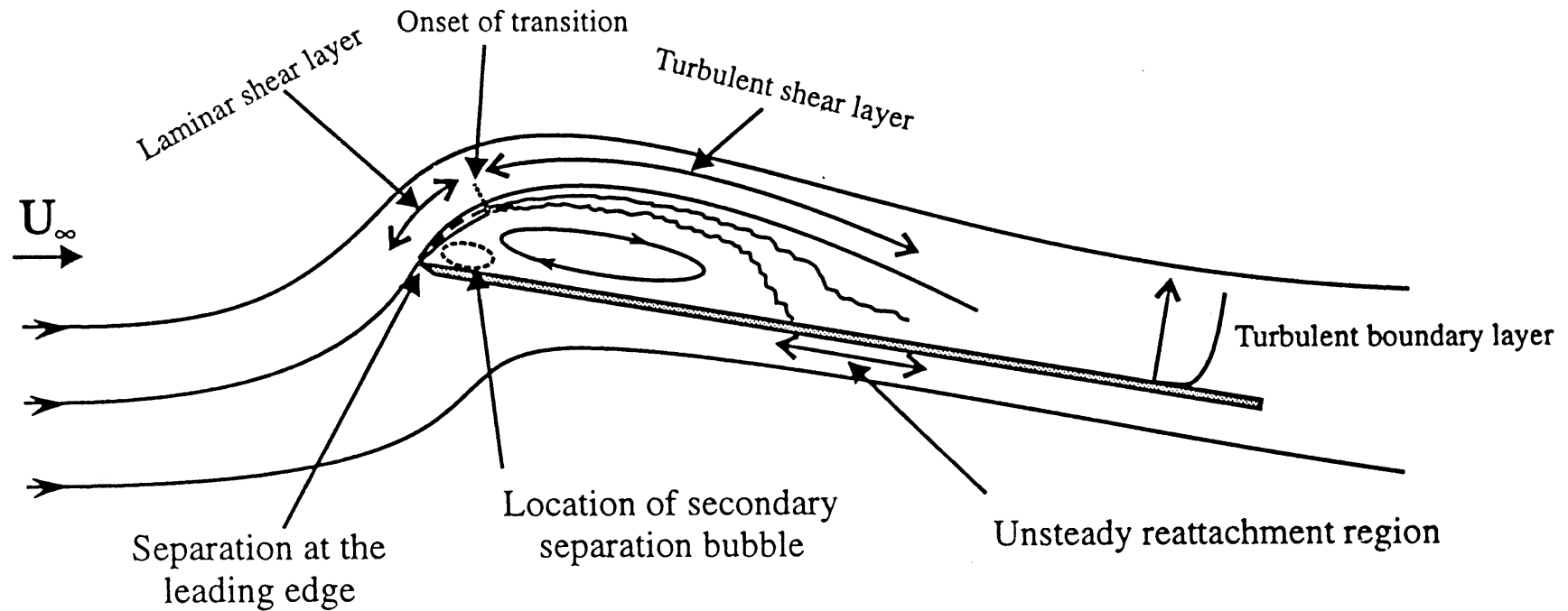
- When the LSB is formed at the leading edge, such as on profiles with a sharp leading edge (sails and plates), the bubble is characterised by a higher recirculation





LSB on plates (long type)

- A secondary separation bubble, which leads to a thicker bubble, is likely to occur

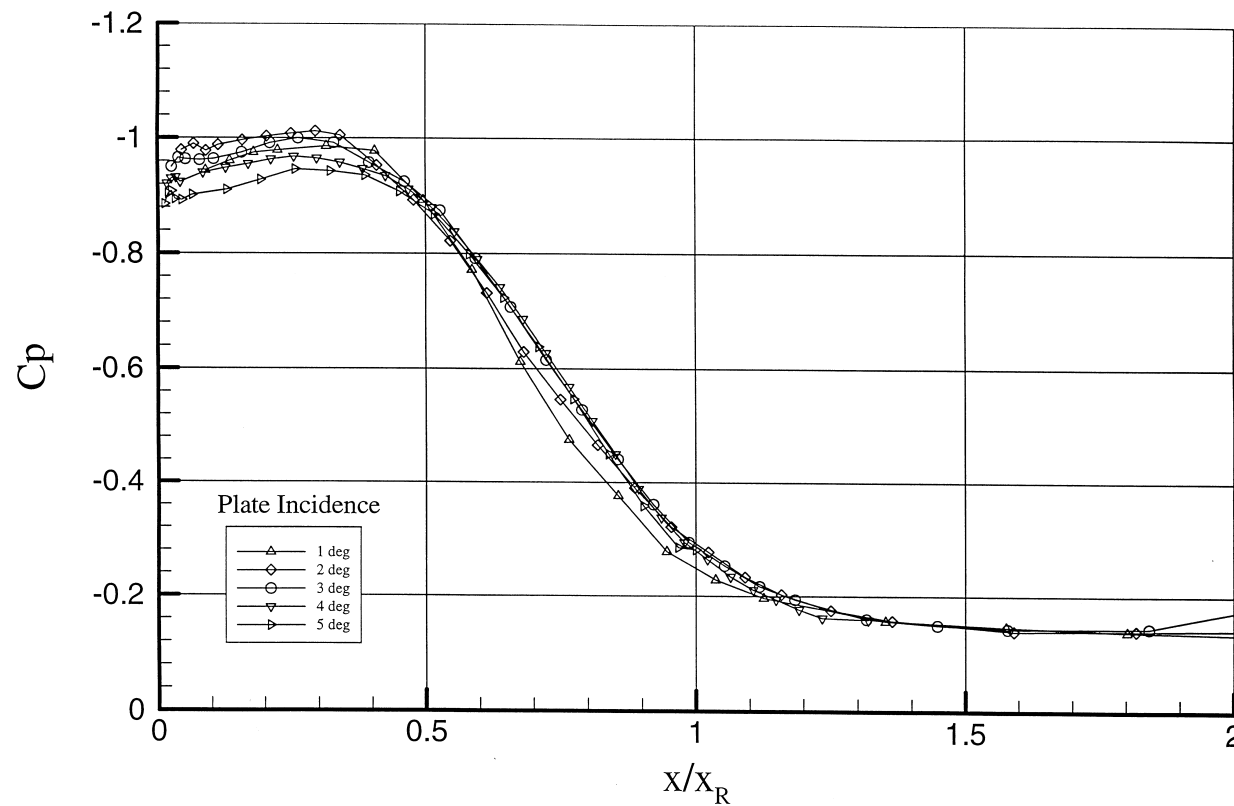


Crompton and Barrett
PIME 2000;2014(G)



LSB on plates (long type)

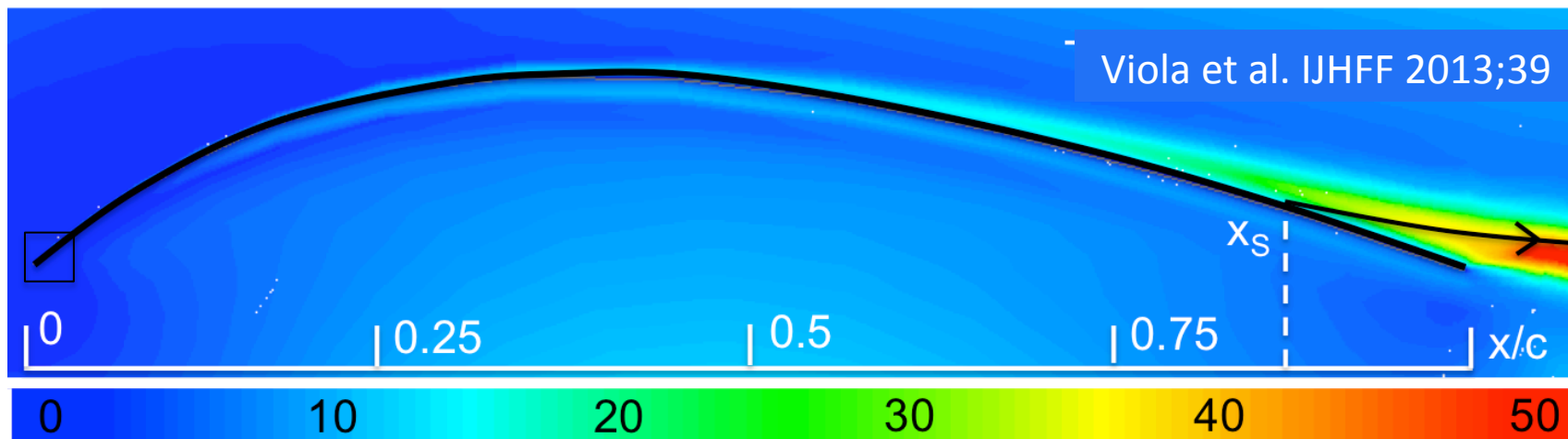
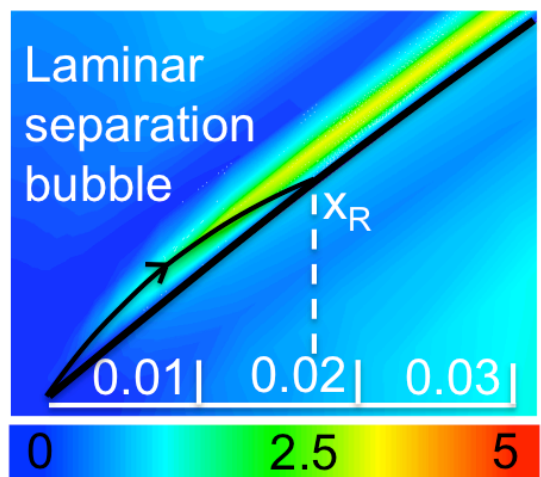
- The pressure plateau typical of the LSB on foils is significantly less pronounced on flat plates



Crompton and Barrett
PIME 2000;2014(G)

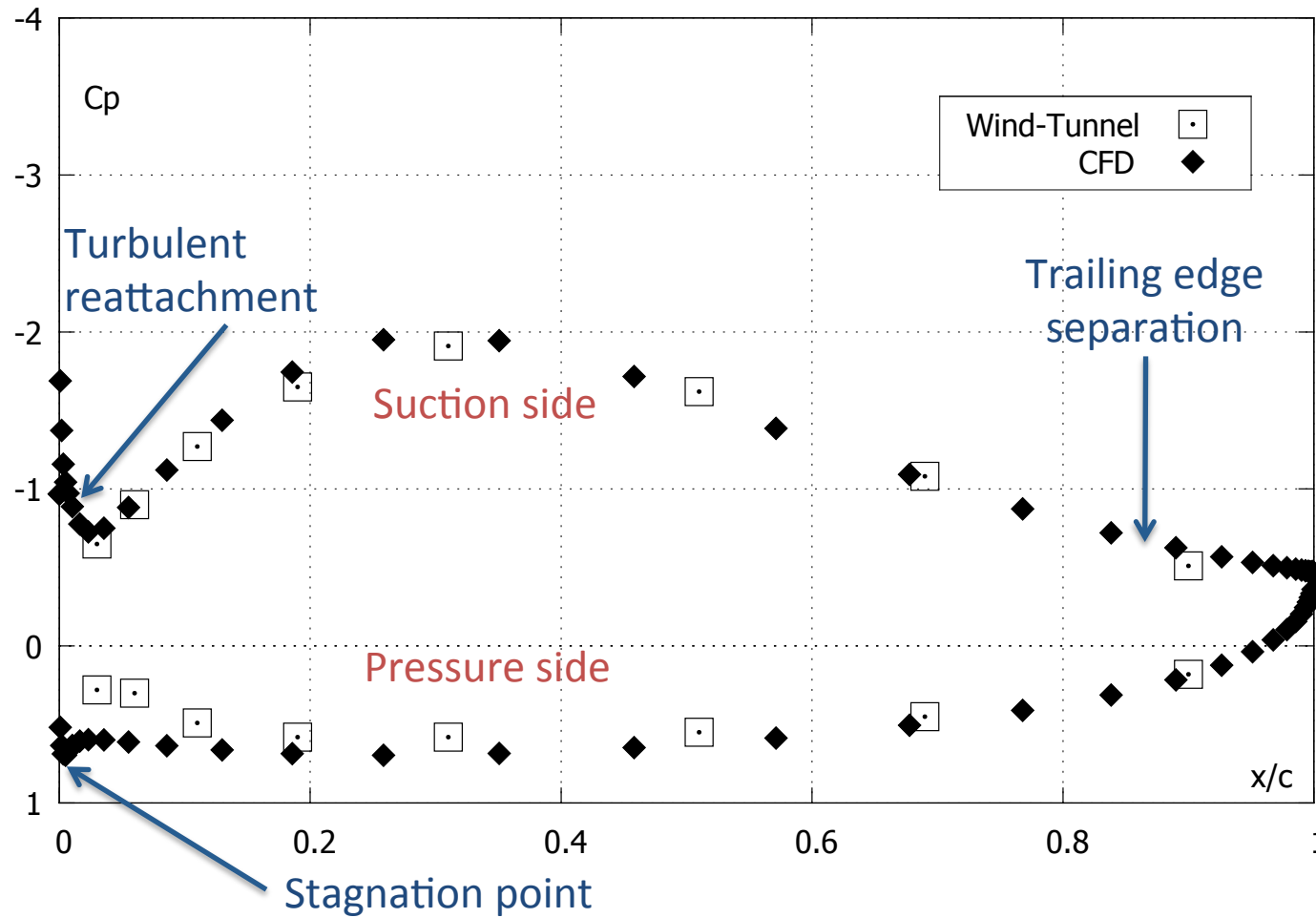


LSB on (upwind) sails



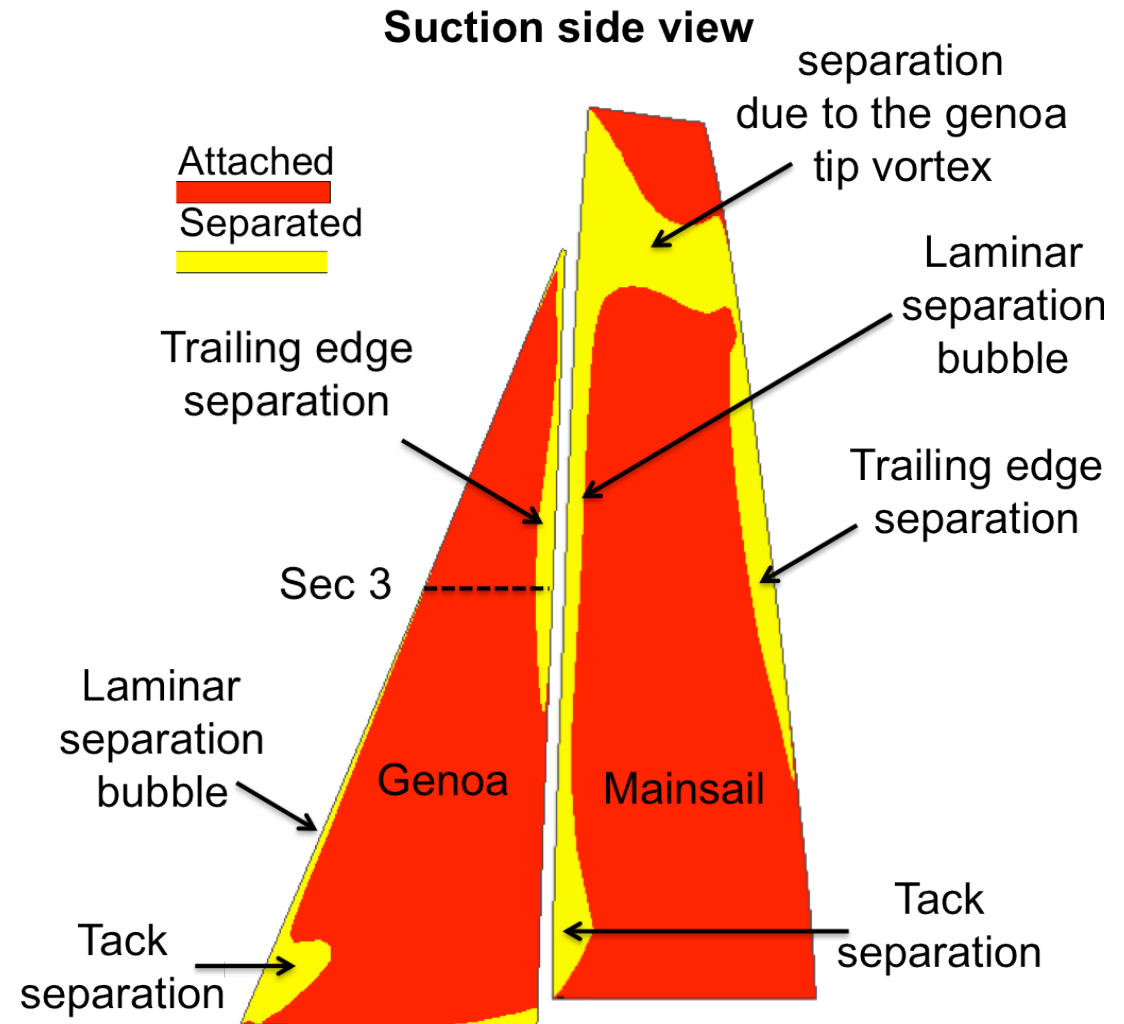
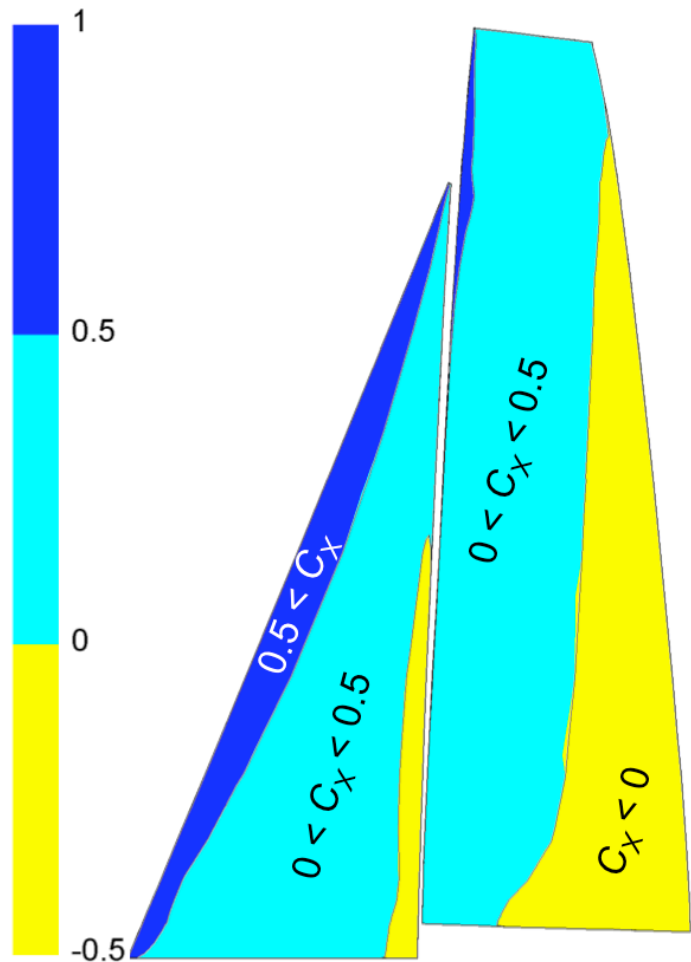


LSB on (upwind) sails





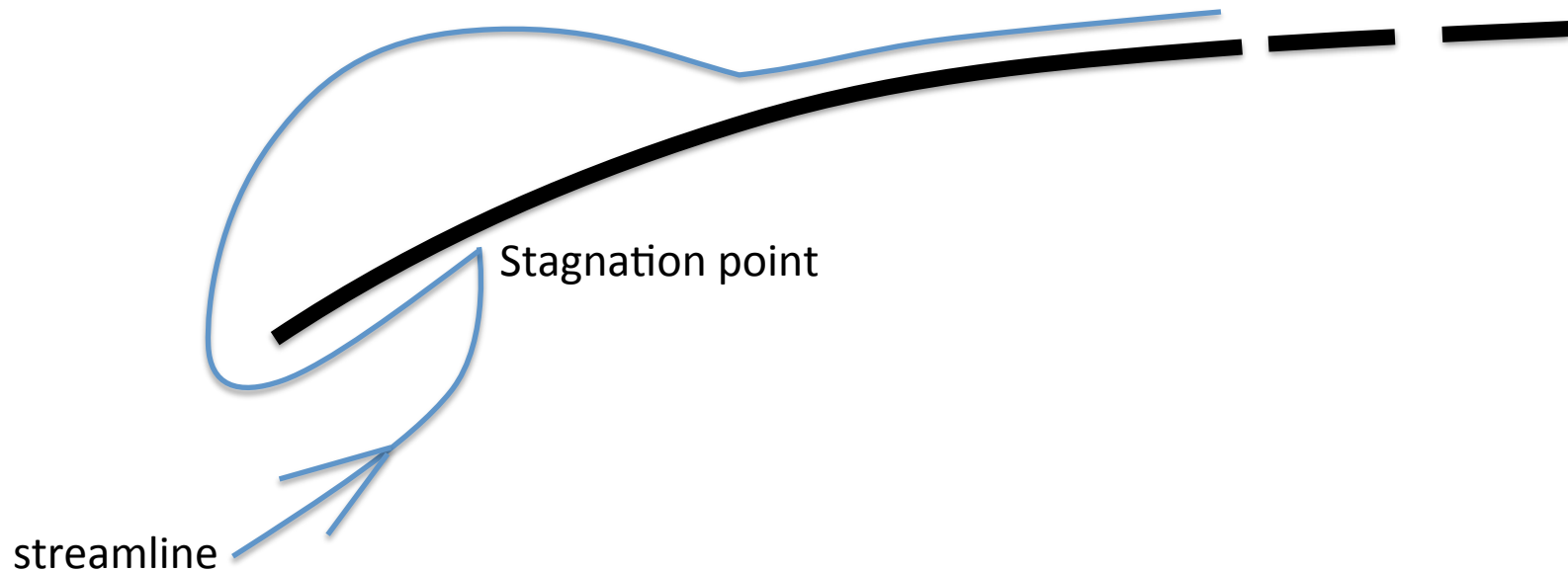
LSB on (upwind) sails





Leading edge separation

- (A) Laminar Separation Bubble
- (B) Leading Edge Vortex

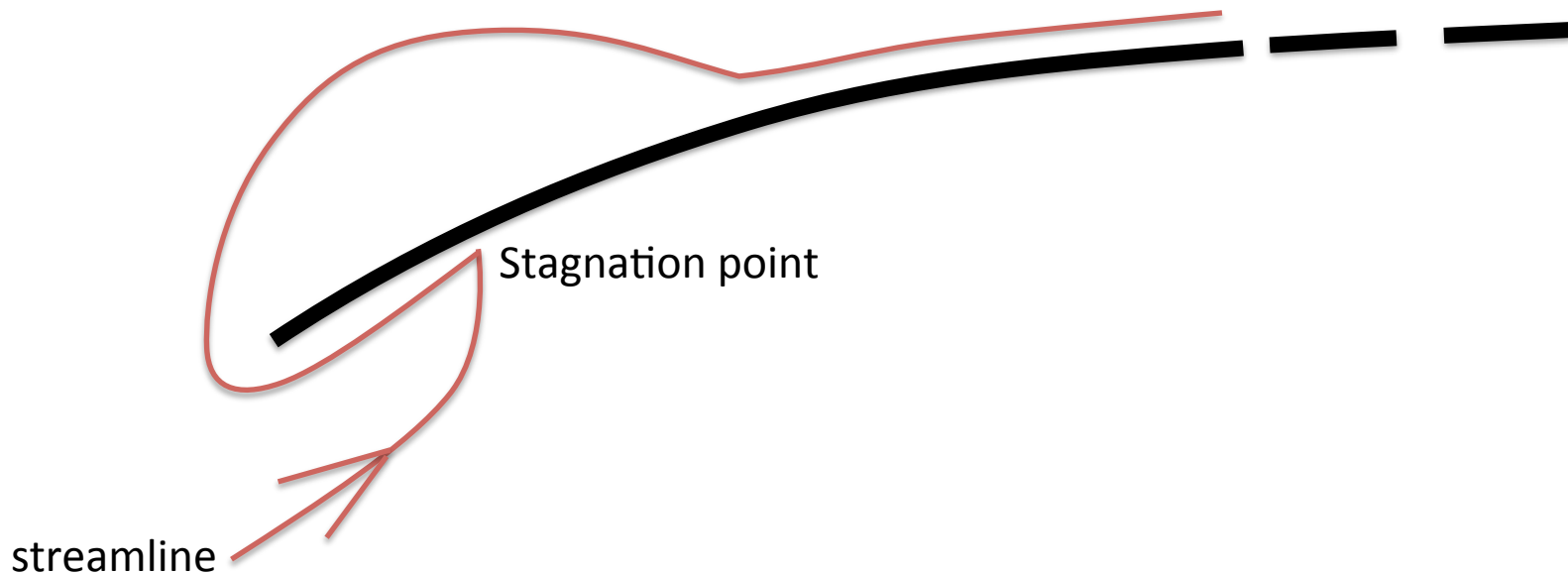




Leading Edge Vortex (LEV)

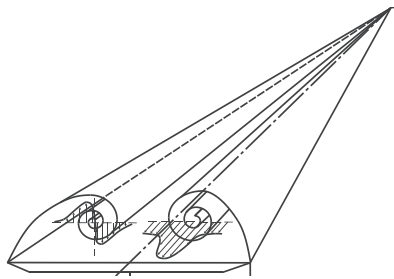
- The LEV was observed for the first time on yacht sails by Viola et al (2013), who performed the first DES on an asymmetric spinnaker
- The LEV is a 3D flow feature whose instantaneous pathlines form a spiral structure
- Vorticity is convected towards the centre of the vortex and extracted from axial velocity at the head of the sail

Time averaged stream line = Instantaneous stream line

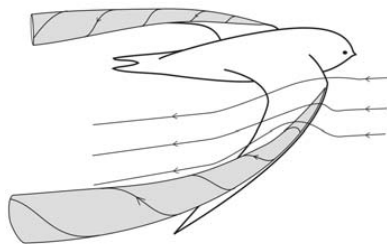




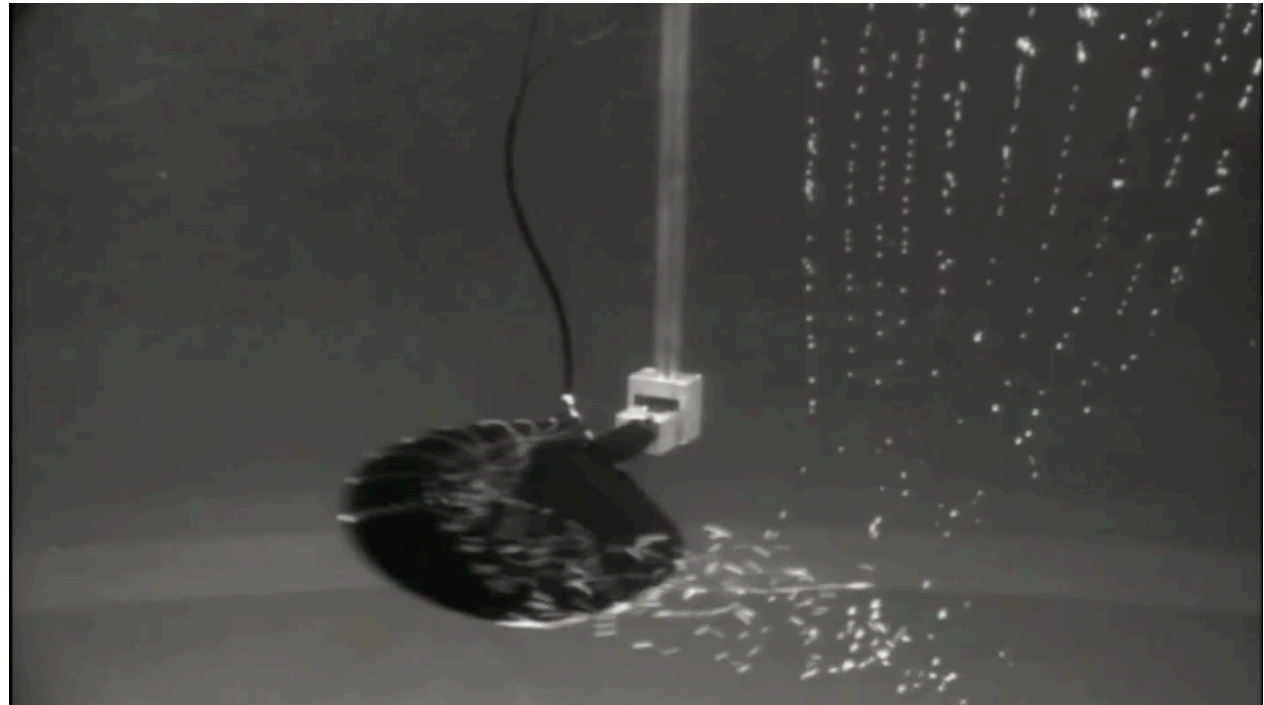
LEV on delta wings and insects/birds



LEV on a delta wing
(Gursul et al., 2007)



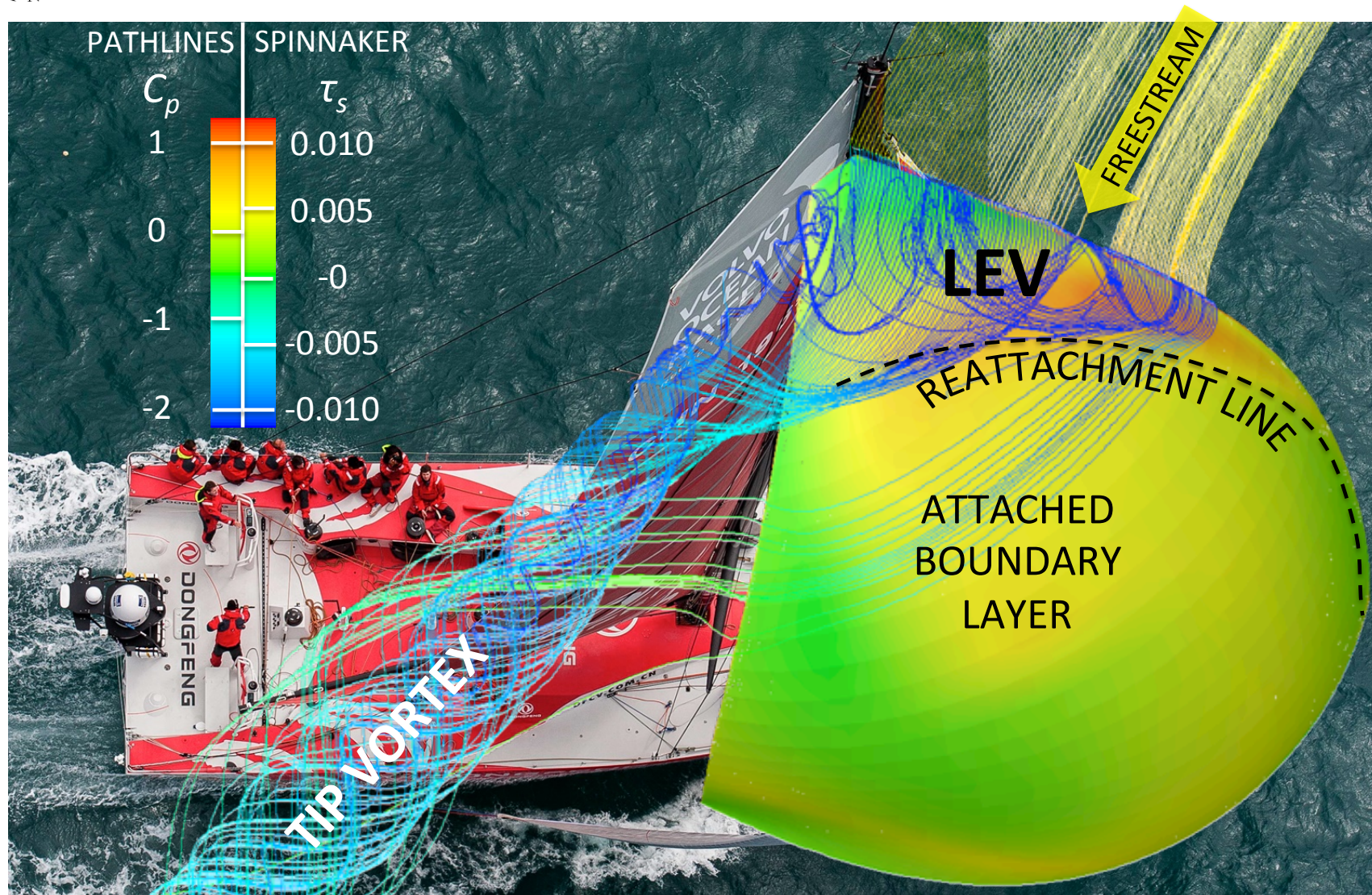
LEV on a bird wing
(Videler et al., 2004)



Lentink Lab (Stanford)

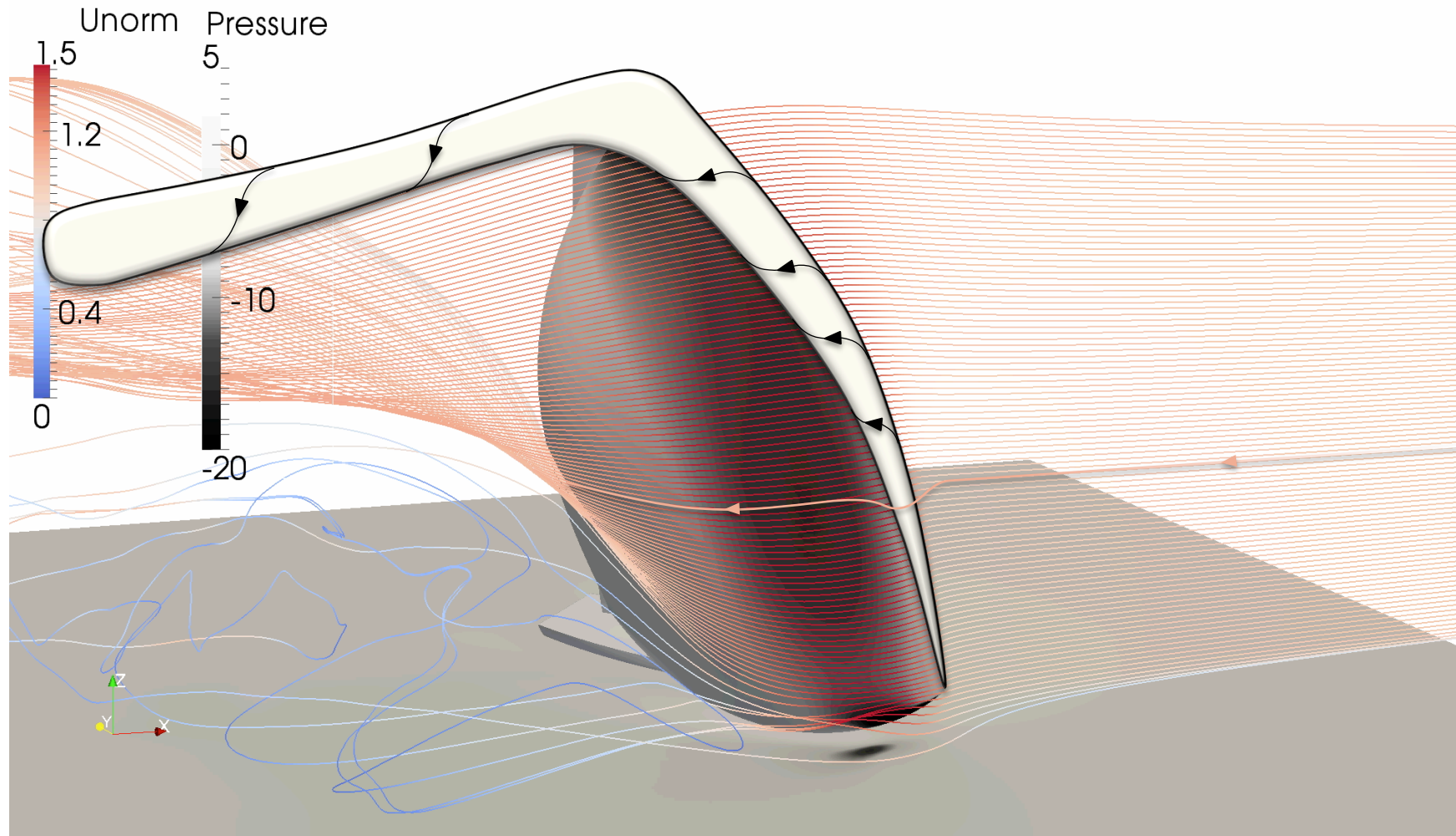


LEV on (downwind) sails



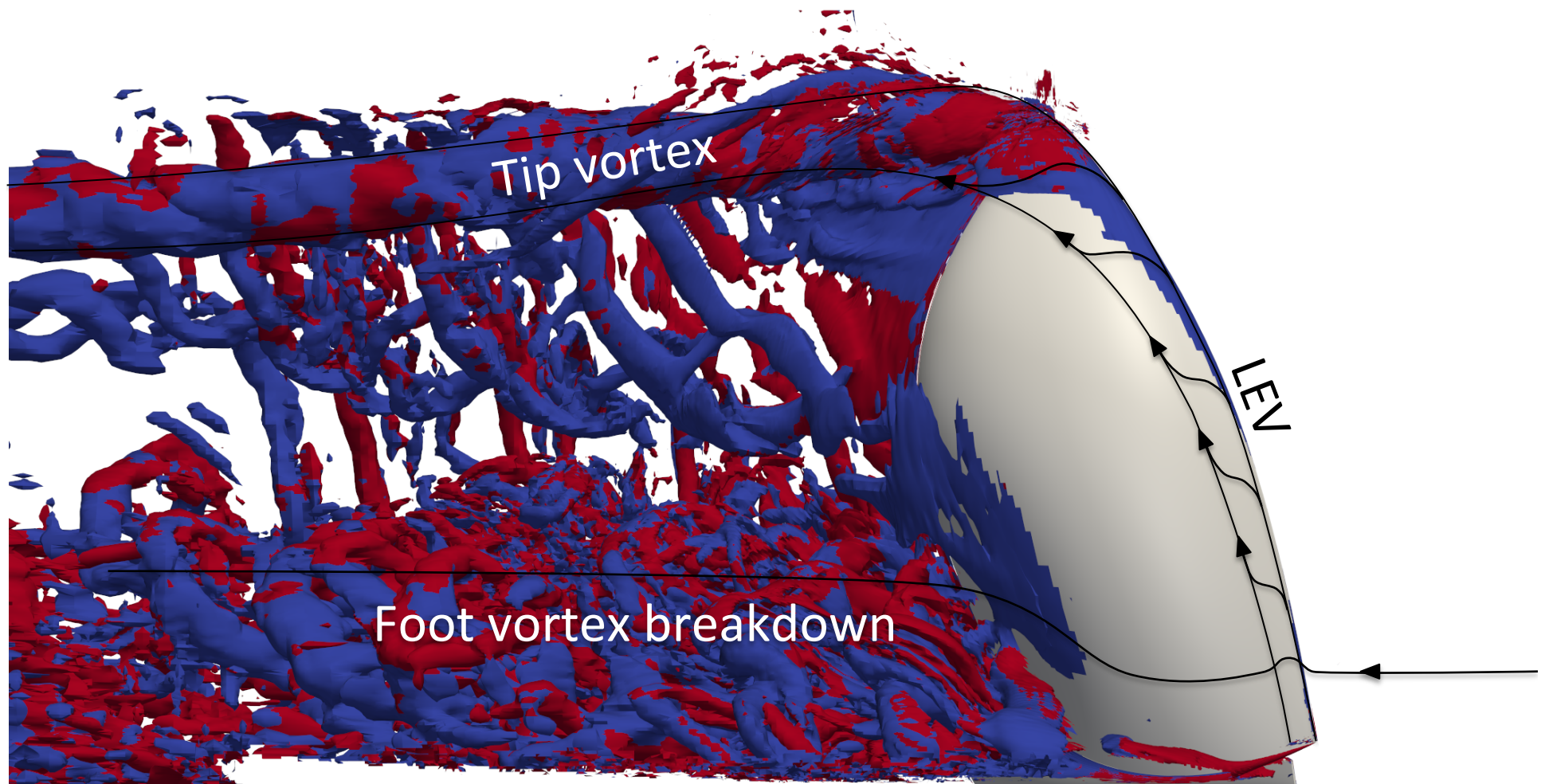


LEV on (downwind) sails





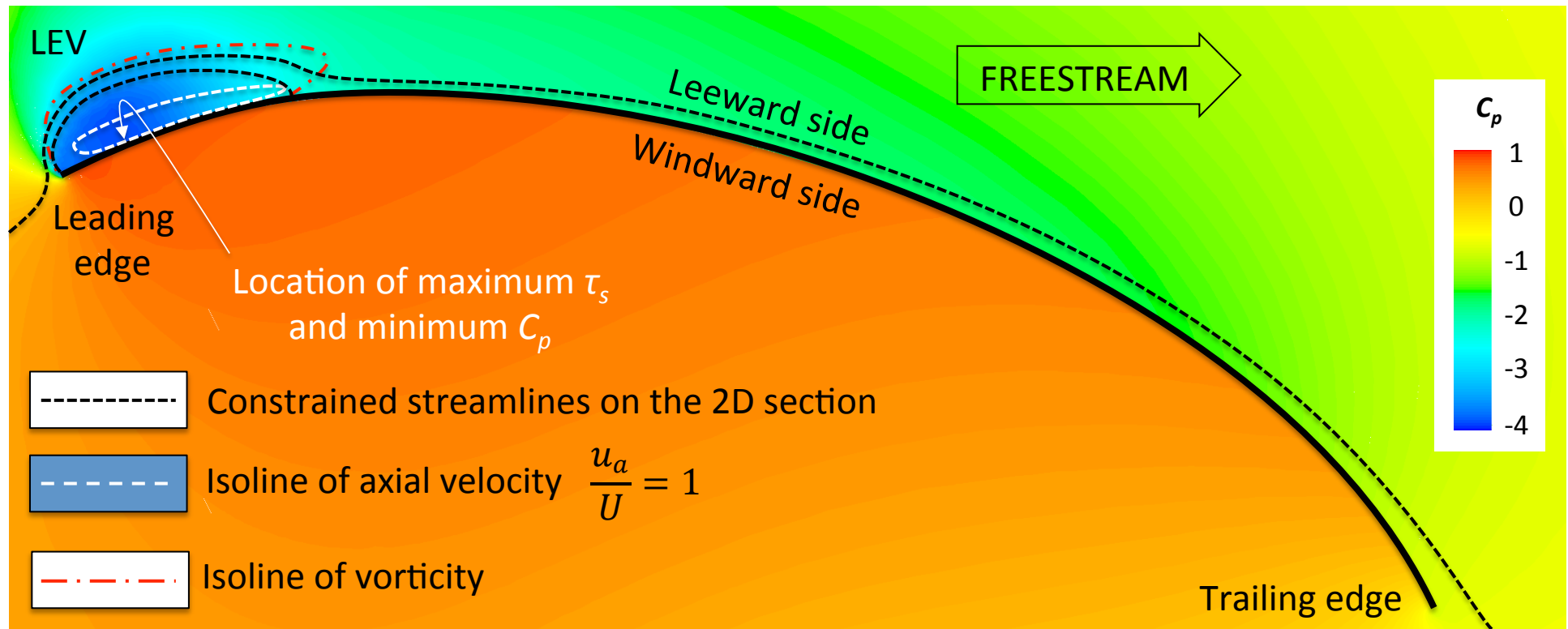
LEV on (downwind) sails





LEV on (downwind) sails

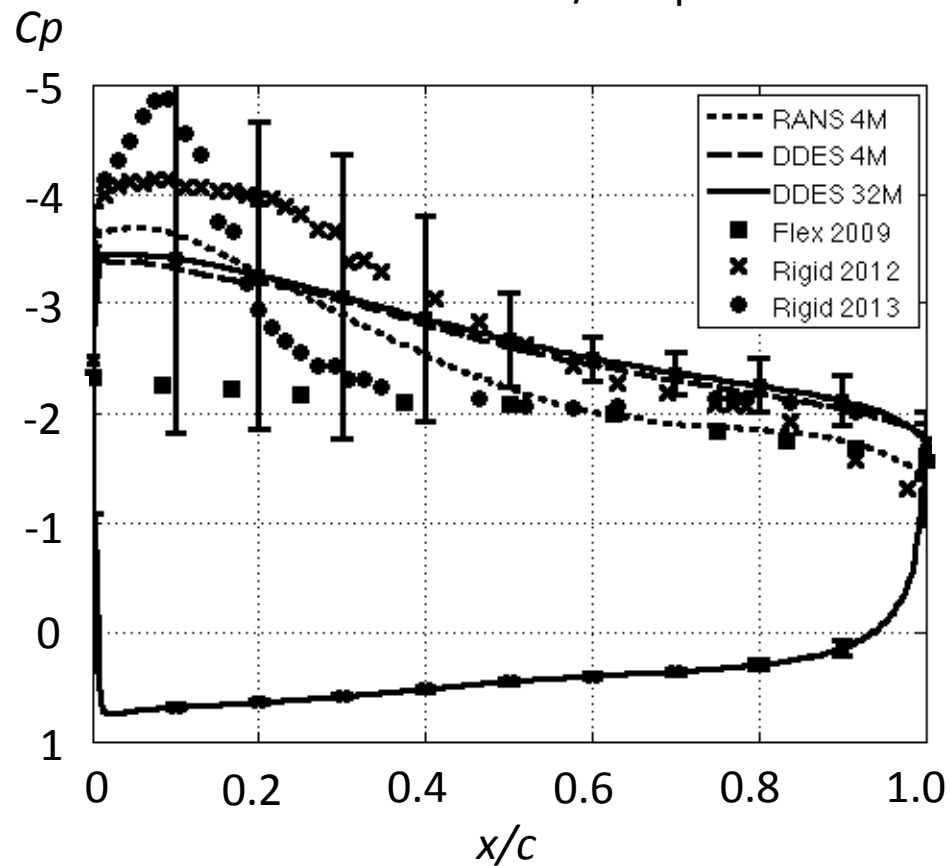
Section at 7/8th span



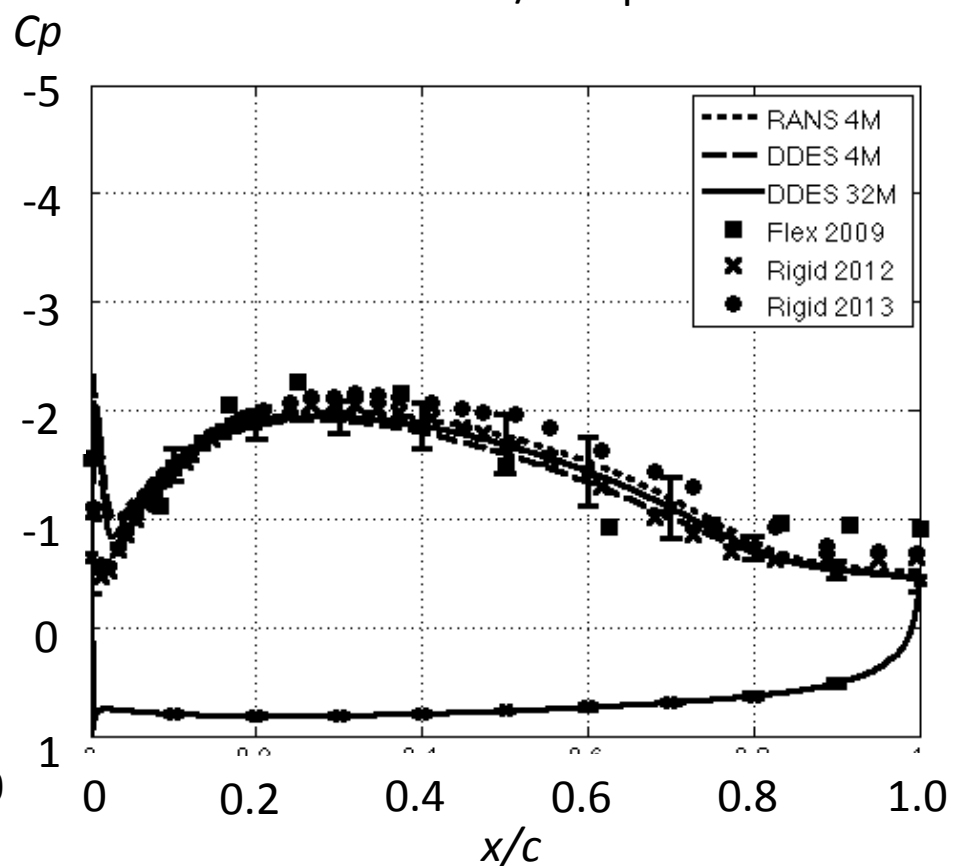


LEV on (downwind) sails

Section at 7/8th span



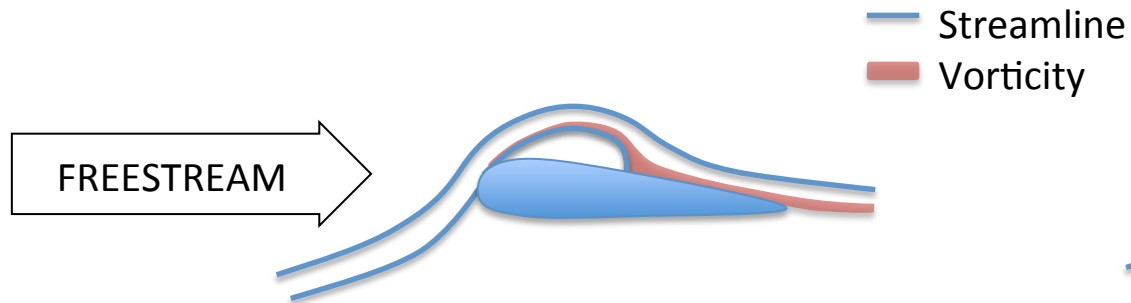
Section at 1/2nd span





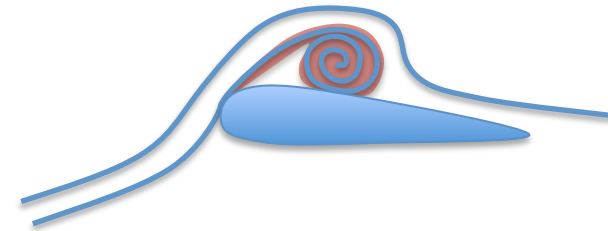
LEV vs LSB

LSB (upwind sails)



Vorticity is convected towards the centre of the vortex and extracted from axial velocity at the head of the sail

LEV (downwind sails)



Discrete pockets of clockwise vorticity are generated from the separated shear layer and are convected downstream



Conclusions

- Sails are 3D THIN CHAMBERED TWISTED FLEXIBLE WINGS experiencing large spanwise velocity gradients and high turbulence
- Leading edge separation and reattachment occur
 - LSB has been computed (non measured) on upwind sails
LSB is thin and narrow, leading to a minor effect on pressure
 - LEV has been computed (non measured) on downwind sails
LEV grows toward the tip leading to large suction and uplift shear
- Trailing edge separation may occur
- Forces on sails can be predicted within the experimental uncertainty
 - Upwind sails: $\pm 1\%$
 - Downwind sails: $\pm 20\%$
- Effect of flexibility and Reynolds number on near-wall flow are unknown



Acknowledgments

Research group

- Susan Tully (RA)
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